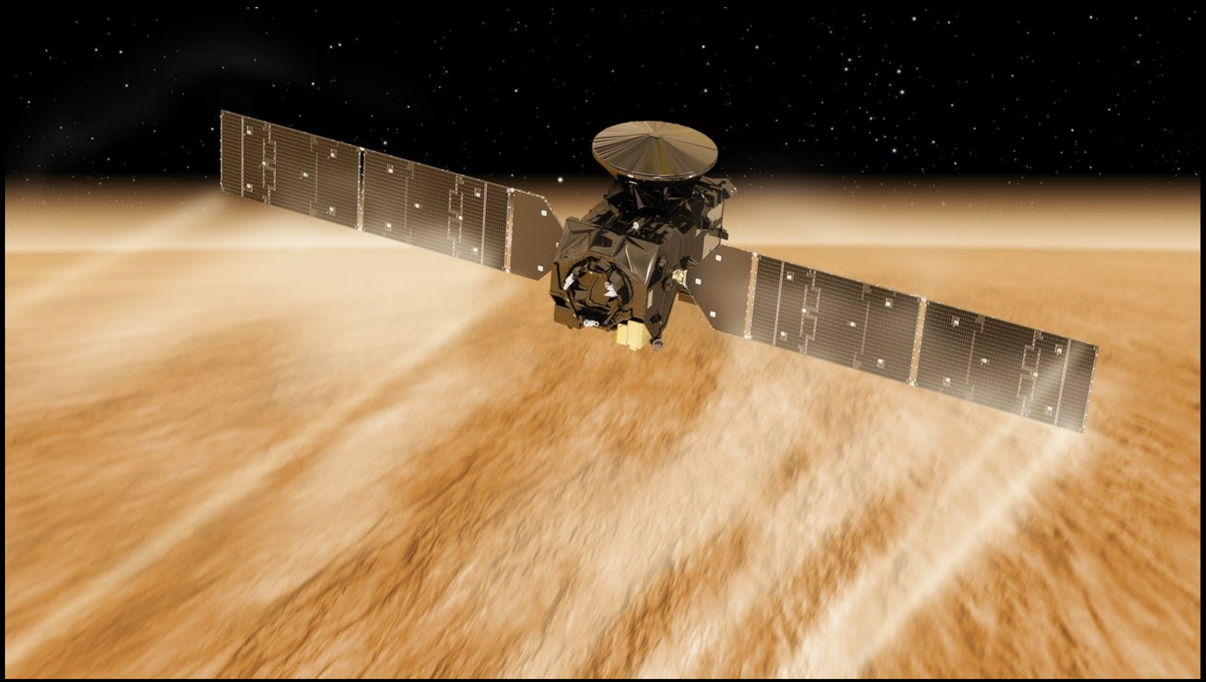
Aerobraking the ExoMars TGO: The JPL Navigation Experience



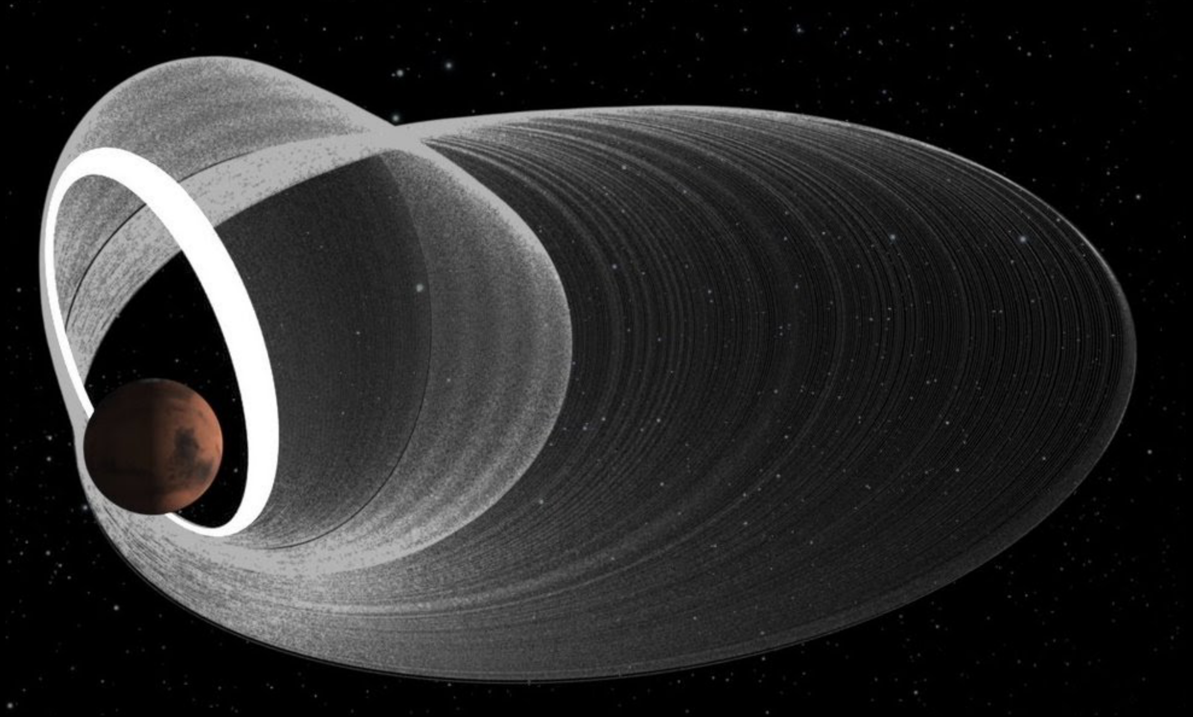


Image Credit: ESA media lab

ISSFD 2019

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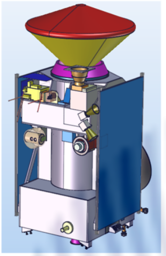
ESA’s ExoMars TGO Mission Summary

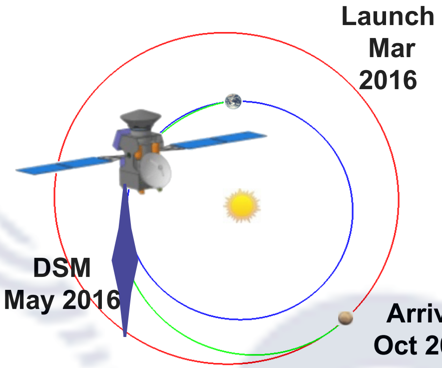
LAUNCH

Mar 14, 2016 from Baikonur, Russia



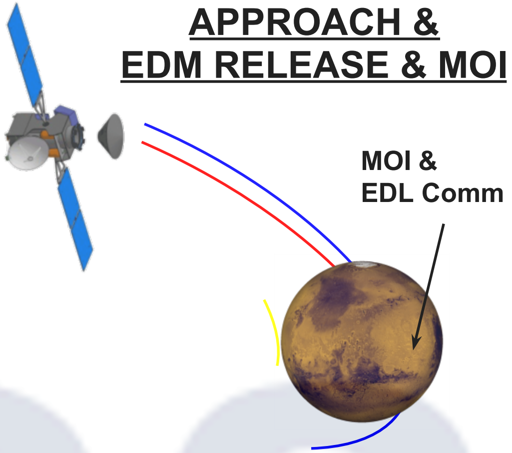
EMTGO in launch configuration

INTERPLANETARY CRUISE



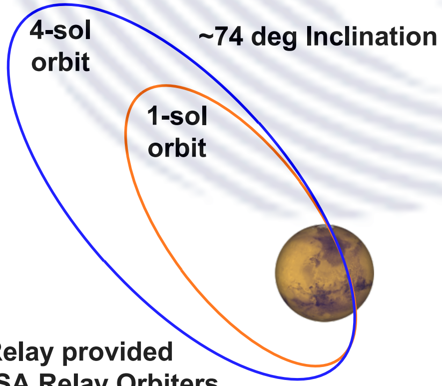
Type II Trajectory: C3 = 7.44 km^2/s^2

APPROACH & EDM RELEASE & MOI



- EDM release at MOI - 3 days
- Orbiter retargets to MOI altitude
- MOI (Oct 19, 2016) captures to 4 sol orbit

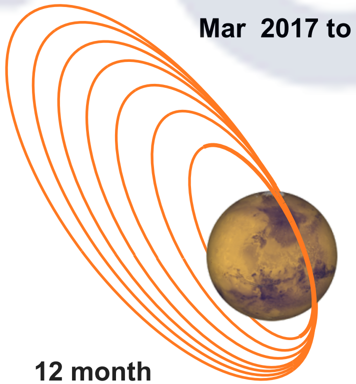
EDM RELAY & TRANSITION TO 1-SOL ORBIT



EDM Relay provided by NASA Relay Orbiters

AEROBRAKING PHASE

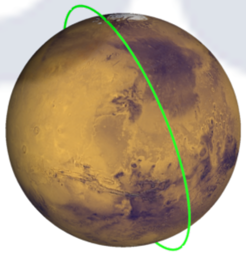
Mar 2017 to Feb 2018



Transition to Science Orbit

12 month Aerobraking

SCIENCE & DATA RELAY PHASE



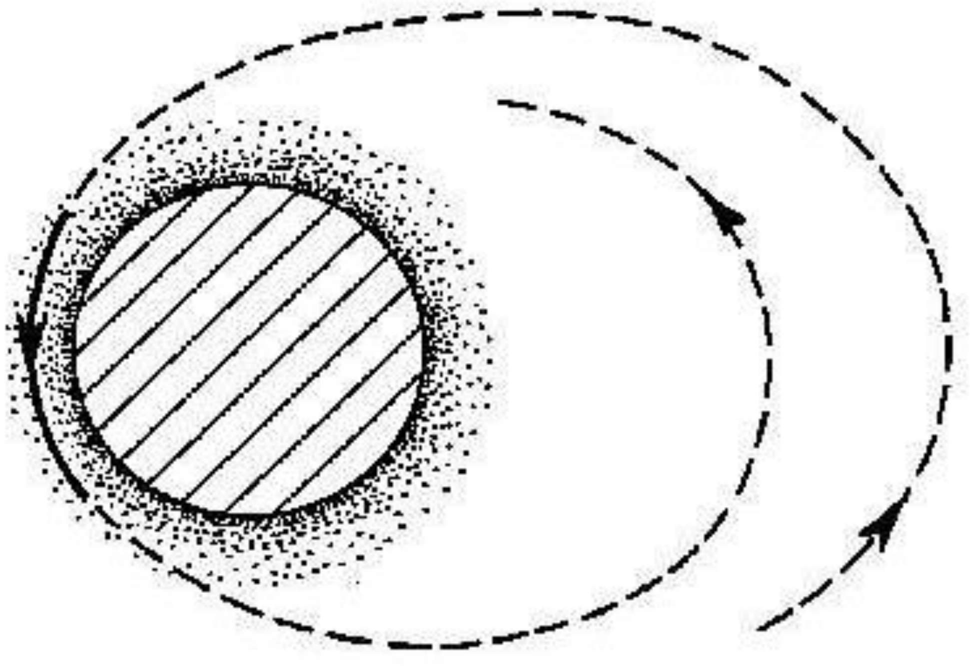
Science & Relay Orbit
- 400 km Frozen
- Rotates every 4 months

- Science Phase: 1 Mars Year
- Relay Phase: ExoMars 2020 & Mars 2020
- Relay Phase: Future Missions through 2022

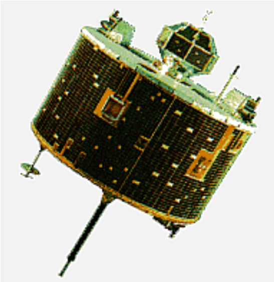
Aerobraking

ExoMars TGO

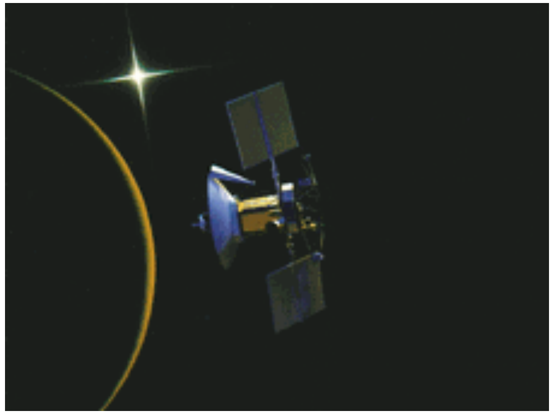
- Aerobraking is used when a spacecraft requires a low orbit after arriving at a body with an atmosphere, and it requires less fuel than does the direct use of a rocket engine.
- Aerobraking reduces the high point of an elliptical orbit (apoapsis) by flying the vehicle through the atmosphere at the low point of the orbit (periapsis). The resulting drag slows the spacecraft.
- Typically used repeatedly over a period of months.
- Ground operations required for Mars missions due to significant atmospheric variability and no GPS.



History of Aerobraking Missions

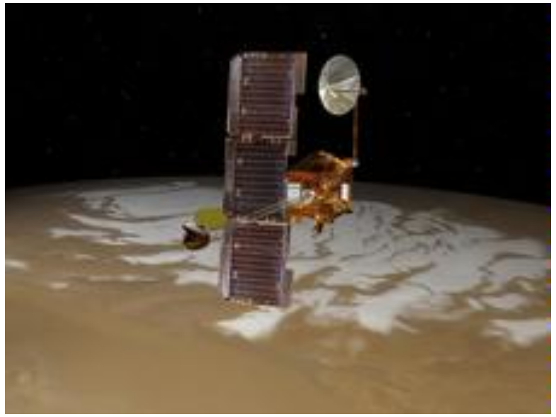


Hiten – Earth/Moon
1991, Japanese

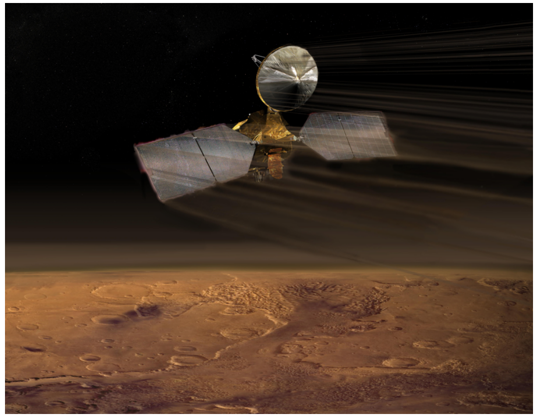


Magellan – Venus
1993, NASA

Mars Global Surveyor
1997-98 NASA



Mars Odyssey
2001-02, NASA

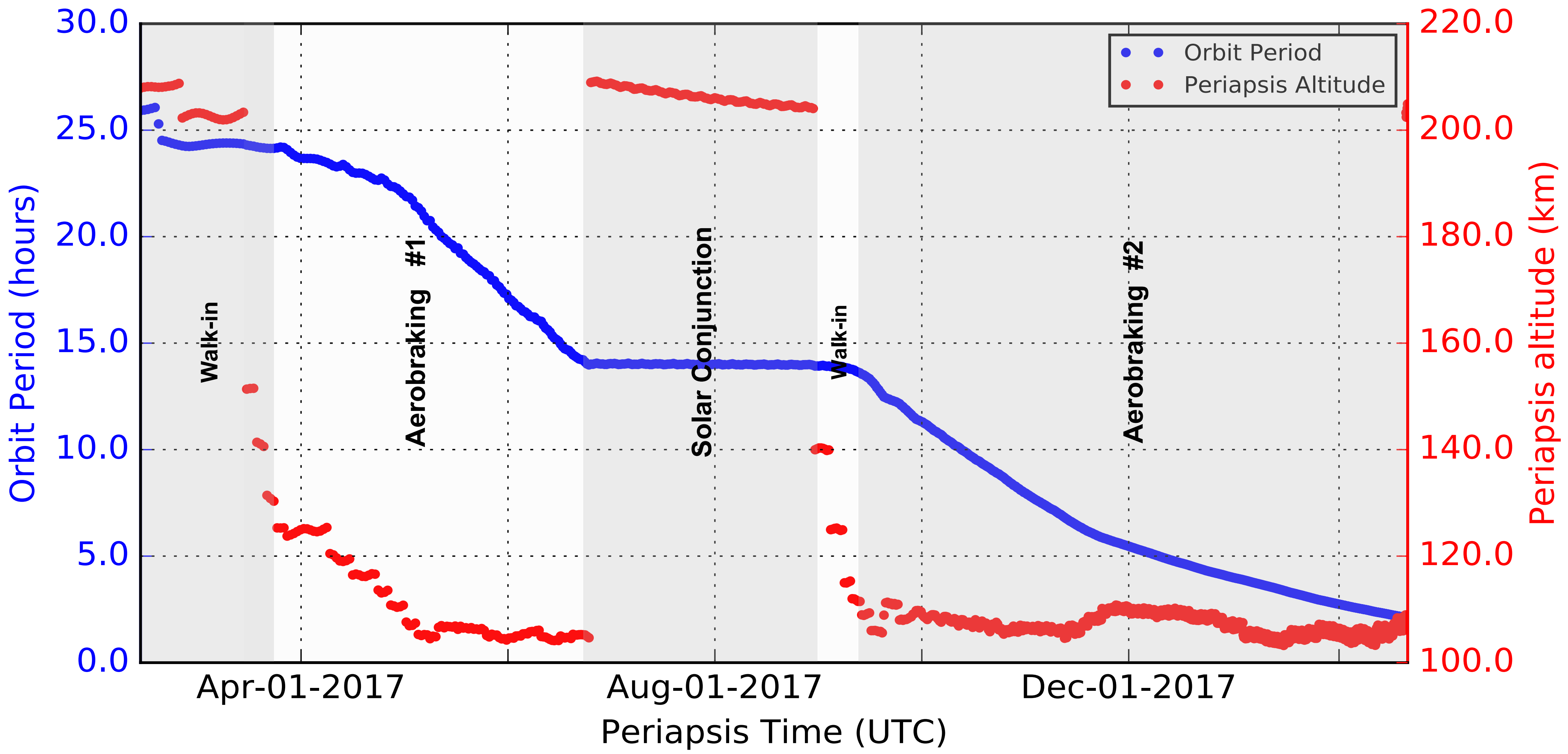


Mars Reconnaissance Orbiter
2005, NASA

Venus Express – Venus
2014, ESA

TGO Aerobraking Phase

ExoMars TGO

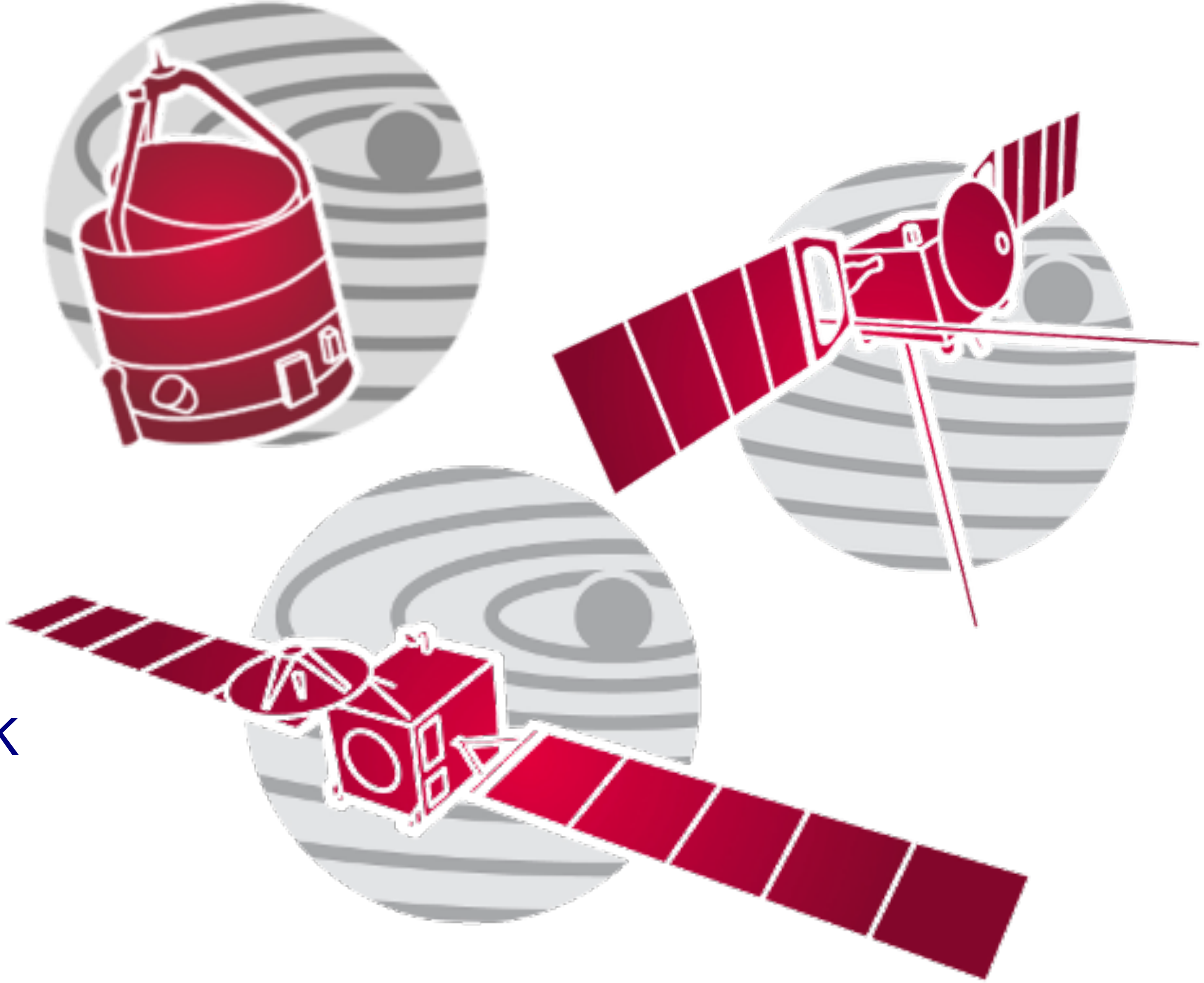


JPL Navigation & ESOC Flight Dynamics Collaboration

ExoMars TGO

The European Space Agency (ESA) and NASA's Jet Propulsion Laboratory have partnered to provide navigation consultancy and support since 1985

- Giotto to comet Halley in 1985
- Mars Express cruise phase in 2003 (DDOR)
- Rosetta comet approach phase in 2014 (Optical Navigation)
- Rosetta comet landing in 2015
- Tracking data support from ESTRACK and DSN
- Collision avoidance analysis between Mars orbiters



JPL-Nav's Roles during TGO Aerobraking

- Consultancy for aerobraking operations:
  - Technical Interchange Meetings (Nov 2016, Feb 2017, Aug 2017, Jan 2018)
  - Navigation software cross verification
  - Bi-weekly teleconferences
  - Review the strategy for the Walk-in and End-game phase in the area of Guidance Navigation and Control.
  - Provide independent orbit determination solutions during the Walk-in and End-game phase
- Providing Mars atmospheric weather forecast
- Collision avoidance with Mars orbiters

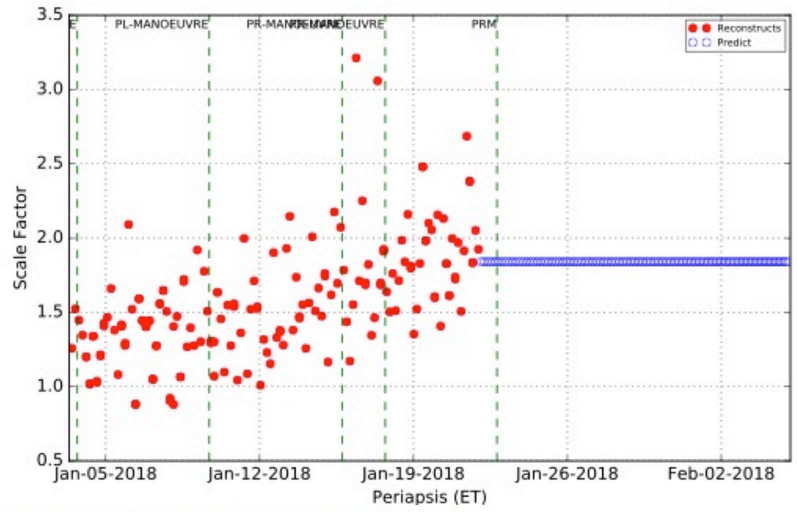
Shadow Navigation

- JPL-Nav produced independent Orbit Determination (OD) solutions.

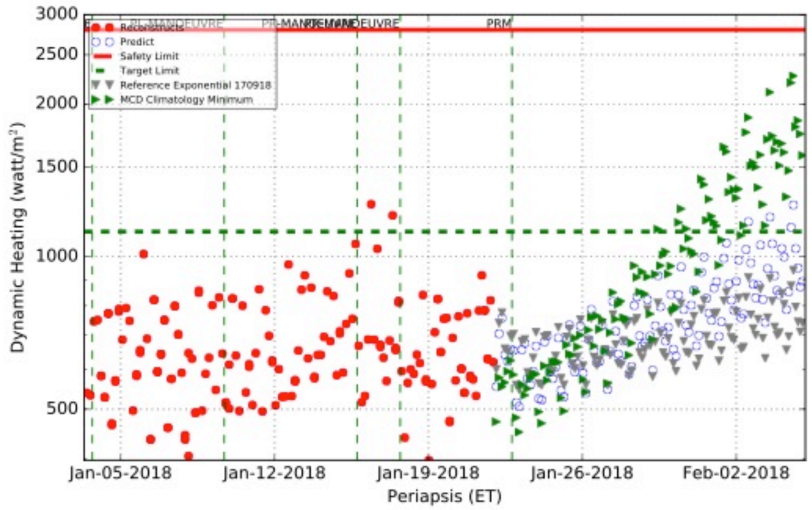
- During the end game, JPL-Nav provided manual OD solution once a day, effectively covering ESOC-FD's night shift.

- In addition to once a day manual OD, a robust automatic "quicklook" OD system was used to inform ESOC-FD and JPL-Nav of any troubling developments instead.

JPL Scale Factor History and Predict



Peak Heat Flux History and Predict



Navigation Data Exchanges

ExoMars TGO

ESOC-FD to JPL-Nav

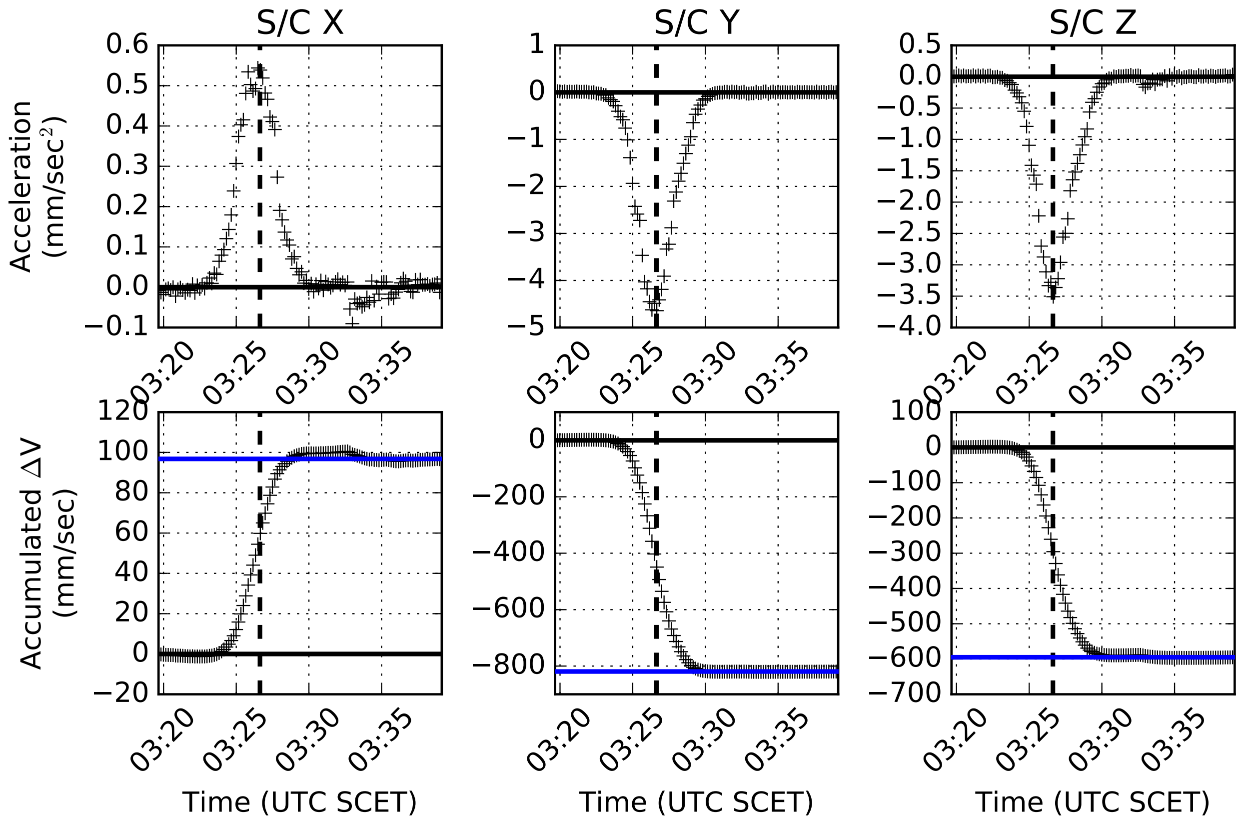
- Spacecraft physical data
  - Geometric, optical properties, mass, etc.,
- Spacecraft dynamic data
  - Event log, thrust pulse file, accelerometer data
- Maneuver plan
  - Future maneuvers and predicted trajectory. Popup maneuver and Heat Flux reduction maneuver
- Tracking and calibration data
- OD solution

JPL-Nav to ESOC-FD

- OD solution
  - Reconstructed trajectory
  - Summary of OD solutions
  - Post-fit Doppler residuals
  - Prediction parameters for orbit propagation
  - OD report

Using Accelerometer Data

- On-board accelerometers provide independent measurement of drag ΔV
- Efforts to integrate into Doppler-based OD batch filter previously unsuccessful
- New method implemented using accumulated ΔV measurements [Young 2018]
- Proposed for Maven but first implemented on TGO, by both JPL and ESOC teams
- Success led to implementation and use in Maven aerobraking starting in February 2019



Quicklook OD Summary Report (example)

ExoMars TGO

TGO Quicklook Summary: 01116-01121

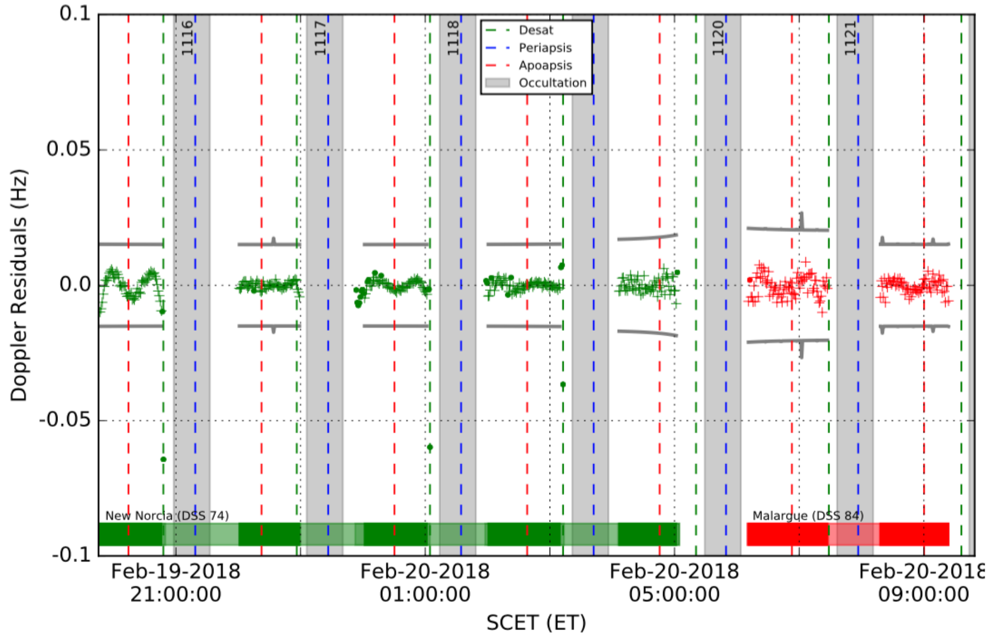
Directory: /nav/tgo/ops/od/quicklook/01116-01121
Start: 19-FEB-2018 19:45:30 ET
DCO: 20-FEB-2018 09:48:55 ET
Runout: 27-FEB-2018 09:48:55 ET
Iterations: 3

Orbit	Epoch	Density (kg/km3)	Alt. (km)	SF (Est.)	SF (Ref.)	DV (mm/s)	Dyn. Pres. Pa	Dyn. Heat W/m2	Heat Load kJ/m2
01116	19-FEB-2018 21:18:37 ET	20.911	106.0	1.317	0.513	1597.901	0.14	508.7	159.7
01117	19-FEB-2018 23:26:36 ET	15.173	106.6	1.058	0.412	1162.973	0.		
01118	20-FEB-2018 01:34:31 ET	30.072	107.3	2.436	0.934	2325.746	0.		
01119	20-FEB-2018 03:42:09 ET	18.719	108.1	1.787	0.659	1455.124	0.		
01120	20-FEB-2018 05:49:33 ET	12.477	108.7	1.329	0.487	978.041	0.		
01121	20-FEB-2018 07:56:49 ET	9.128	108.4	0.855	0.339	716.253	0.		

Estimated Density: MG2010 MY0
Reference Density: Reference Exponential 170918

Predict Density: MG2010 MY0
Predict ScaleFactor: 1.180

Residuals



Automation of Orbit Determination

ExoMars TGO

- JPL's Quicklook OD process automatically:
  - Imports tracking and auxiliary data by cron task (JPL's Tardis)
  - Selects reasonably long tracking data arcs
  - Filters out anomalous tracking data
  - Chooses the initial epoch
  - Sets up a priori values for estimation parameters (state, atmospheric density scale factors)
  - Runs iteration of estimation and update process until convergence
  - Updates arc every 15 minutes, sending drag parameters after each periapsis
  - Sends summary report to JPL-Nav and ESOC-FD every 12 hours
- Two tasks require particular human intelligence
  - Determination of convergence
  - Doppler data editing algorithm

OD Automation: Popup Watchdog

- TGO was capable of autonomous popups
  - Small 3 km flux reduction maneuvers (FRM) or larger automated popups (APM)
  - ESOC-FD requested that JPL-Nav report quickly if one was observed, including in off hours
- Detection of popup maneuver was made by comparing solutions with/without popup maneuver included in the OD
- Sent notification email if:
  - Residuals of with-maneuver case were smaller than no-maneuver case
  - Significant change between with- and no-maneuver cases (protection against invalid data)
  - Reasonably small residuals in no-maneuver case (protection against invalid data)

Conclusions

- TGO successfully entered into final science orbit in April, 2018, using one year long aerobraking to reduce the orbit period from 24 hour to 2 hour.
- Collaboration between ESOC-FD and JPL-Nav contributed to the successful completion of this challenging aerobraking operation.
- JPL-Nav provided consultancy in aerobraking navigation operations, daily OD solutions during end game, and autonomous quicklook OD solutions for early warning.
- JPL-Nav also benefited from this cross-support experience, gaining operational training and opportunity of process revision for JPL’s next aerobraking mission (MAVEN).